Effect of Operator Position on the Incidence of Continuous Mining Machine/Worker Collisions

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Remote operation of continuous miners has enhanced the health and safety of underground miners in many respects; however, numerous fatal and non-fatal continuous miner struck-by accidents have occurred when using remote controls. In an effort to prevent these injuries, NIOSH researchers at Pittsburgh Research Laboratory examined the workplace relationships between continuous miner operators and various tramming modes of the equipment using motion captured data, predicted operator response times, and field- of- view data to determine causes of operator-machine struck-by events in a virtual mine environment. Factors studied included machine speed, direction of escape, operator facing orientation relative to the machine, work posture, distance from machine, and operator anthropometry. Close proximity to the machine, high machine tramming speeds, a right-facing orientation and operator positioning near the tail all resulted in high risk of being struck. It is hoped that this data will provide an improved rationale for operator positioning for remotely operated continuous miners.

INTRODUCTION

The Mine Safety and Health Administration (MSHA) reports that both fatal and non-fatal remote-control continuous miner (figure 1) accidents are averaging 284 per year for 1999-2004 during routine mining activities, with the majority of accident victims working within the turning radius of moving continuous miners. The mining industry uses an educational aid called "Red Zones are No Zones" to help operators of remotely controlled vehicles, such as continuous miners, understand which areas around the machine to avoid (see figure 2). Fatalities and injuries regrettably continue as a result of making contact with moving machines. MSHA is interested in reducing injuries and fatalities attributed to the operation of continuous mining machines (Clark et al. 1998, Colley et al. 2006). As recently as February 2006, MSHA posted on its website information regarding protection of CM operators by using proximity warning devices to help recognize the red-zone strategy.

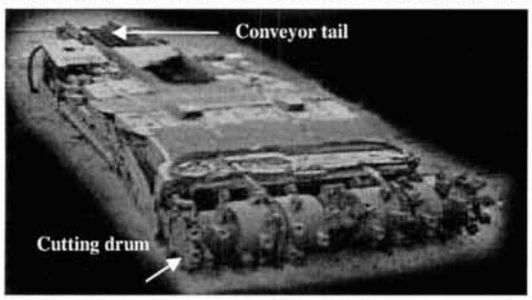


Figure 1 – Continuous miner

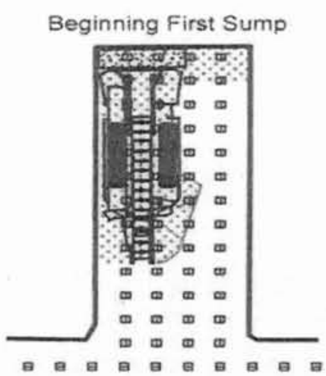


Figure 2 - Red zone around a continuous miner

In an effort to better understand the influence of these issues on the risk of injury on operators not adhering to the red-zone strategy, it was decided that a digital human model (DHM) approach would be a useful methodology. The purpose of this investigation was to analyze factors influencing struck-by accidents during tramming of a continuous mining machine using DHM simulations driven by actual human motion analysis with a variety of subjects, postures, facing orientations, environmental constraints, and machine characteristics. The DHM used MSHA fatality information to validate the model parameters relating to operator position. Survival analysis of the results allowed an evaluation of a complex interaction of multiple parameters as they change over time. The fact that some of the scenarios simulated in this DHM study involved positions in the red zones does not imply that it is ok to operate a continuous miner there.

METHOD

Motion Analysis Data

Ten male subjects aged 32-59 years were recruited from the local mines to perform realistic movements in a laboratory setting (figure3) that mimic getting out of the way of a

Figure 3 – Laboratory test setup

moving machine. The subject's motions were measured by recording them using Motion Analysis Corporation's (MAC) motion tracking and capturing system.

Human motion data were obtained from various operator work postures and escape paths (directions) typically used around tramming operations of underground remote-controlled mining equipment such as continuous miners. The

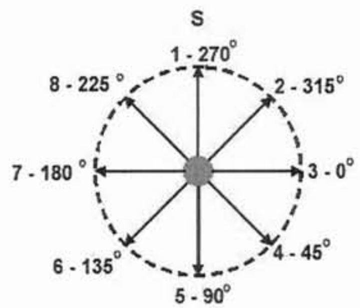


Figure 4 – Test area layout showing path number and orientation in degrees

tests were conducted using kneeling on two knees, squatting and standing postures that represented seam heights 36-, 48- and 60-inch, respectfully. At a given signal, a test subject moved in a given test posture from a starting location (see figure 4, solid circle) as quickly as possible along a given path (numbered 1 thru 8) labeled on a carpet (Figure 3). The sequencing of path direction was randomized for each subject. Prior to each path movement, the subject's orientation was either facing the signal source (S) or with the signal source to the subject's left or right side. When a light source at 'S' was turned on it cued the test subject to move. The subject stopped moving once he crossed the outer portions of the dash-circle (figure 4) on the carpet.

Development of Human-Machine Model and Simulation Data Collection

A human-machine model (figure 5) was developed to provide the means to measure parameters that would be used to predict struck-by events when the operator tries to move out of the way of the moving machine. The output parameters included: (1) the time when the machine first begins to move, (2) the time when the operator first begins to move, (3) the

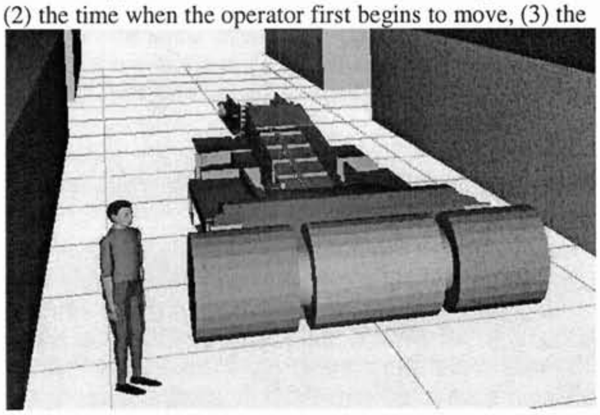


Figure 5 – Human-machine model contains a continuous miner model and a digital human model of an operator.

time when the operator is struck-by an object, (4) name of the object that struck the operator, and (5) the operator's distance from the start position when struck-by an object. MSHA's fatality report (Dransite and Huntley 2005) provided basic information to help validate the model regarding name of objects that struck the operator, operator's distance and location from the machine at the time of being struck. Struck-by means collision occurs between the operator and machine or the mine wall. The data collection discussed in this paper uses captured motions, simulated scripts and collision detection from Jack digital human modeling and simulation software.

The human-machine model was setup to generate and collect data during simulations from two different work locations: cutting drum or conveyor tail (see figure 1). From these work locations simulation scripts were programmed to rotate the machine (4.77, 9.55 and 19.1 deg/s) until it came in contact with the virtual mine wall. In addition, during the machine's rotation, the captured motions of an operator would move away using one of the escape paths from the machine starting from a specific distance at one of the work locations. The operator movements were constrained to a digital human model by using capture motion data of test subjects discussed in the previous section. The operator was placed at 0.3, 0.6, and 0.9 meter intervals from the conveyor tail or cutting drum. Captured motions of the experienced equipment operators were replayed in Jack software in the various combinations of kneeling, squatting and standing work postures, facing orientations and escape path directions. Only escape paths 4, 5, 6 and 7 (Fig 4.) were used because they offered at least one direction that cleared the turning radius of the machine at each work location. To present a realistic operator response to the moving machine, researchers programmed the operator's movement using a delayed start in accordance with reaction times reported by Drowatzky (1981) for different age groups that ranged from 0.19 to 0.24 seconds

The simulation database contained 19,440 cases that were collected from ten virtual subjects of which a number of cases involved instantaneous contact information such as collisions occurring at time zero. This happened in the simulation if the operator was already in contact with the machine before it moved or at the instant it began to move. Discounting these, the resulting database for analysis was comprised of 14,308 cases depicting 1,296 possible test scenarios involving machine speeds and direction of rotations, work postures and facing orientations, work locations and distances from the machine, and escape paths.

Variables

Several independent variables were investigated. These variables included the machine speed, operator's distance away from the machine, operator's work posture and facing orientation, operator's work location and escape path direction. Dependent variables included time of a collision

Table 1 - Frequency and cross-tabulation struck-by summary

Work location	Tail	Drum					
% struck-by	76.8	67					
Work Location – Distance[1]	D-1	T-2	D-2	T-1	T-3	D-3	
% struck-by	87.1	87.1	86.1	82.8	71.7	66.1	
Speed, deg/s	19.1	9.55	4.77				
% struck-by	89.9	73	71.7				
Speed-rotation[2]	19 CCW	19 CW	9 CCW	9 CW	4 CCW	4 CW	
% struck-by	91.1	88.9	81.7	64.5	59.6	50.1	
Time[3] (s)	0.1	0.5	1	2	3	4	4.4
Cumulative[4] %	24.6	69.9	85.4	96.4	97.5	99.7	100
Body part	Arms	Head	Legs	Feet			
% struck-by of total[5]	61.4	23.8	11.4	3.4			

[1]Distance from work locations (Tail and Drum) 1-0.3m, 2-0.6m, 3-0.9m

[2] CW = clockwise; CCW = counterclockwise

[3]Time intervals during machine rotation

[4]Cumulative percent of total struck-by events

[5]Percent of total struck-by events

event, part of the body contacted and part of the machine contacted.

Survival Analysis Model

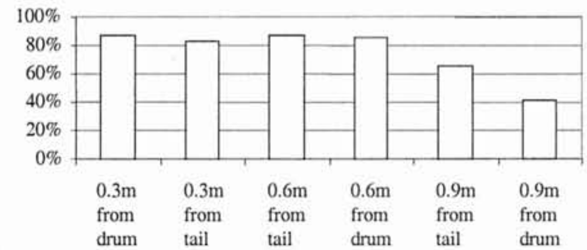
Survival analysis is a tool that allows an evaluation of a complex interaction of multiple parameters as they change over time. In this instance the parameters include machine speed, operator start location, facing direction and posture. The analysis identified the critical parameter interaction that impact operators at a given point in time. A Cox regression model was used to examine the influence of the independent variables on the time to contact. Cases where no contact was made were treated as censored observation. Main effects and all two way interactions were analyzed using a likelihood ratio stepwise technique. Proportional hazard checks were performed at all stages of the analysis. The type I error was set at 0.05.

RESULTS

Frequency and Cross-tabulation

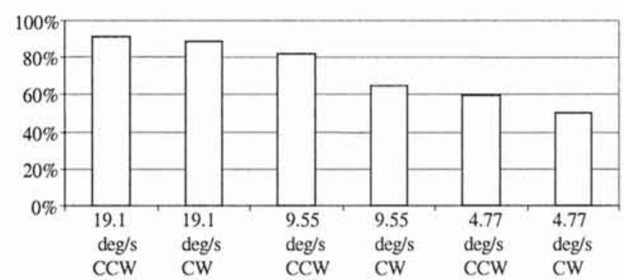
Frequency and cross-tabulation analyses considered 14,308 simulations. Of the simulations examined, 10,254 exhibited struck-by events between the operator and the continuous miner equipment. Struck-by events for some factors were compiled in Table 1, which shows that the operator was struck 76.8% of the time when working at the tail location. The table also includes cross-tabulations, for instance, the operator was struck 91.1% of the time when the machine moved counterclockwise at a speed of 19.1 deg/s. The cumulative percent of total struck-by events per time while the machine moved and percent of the total struck-by events, when a body part on the operator was most frequently contacted, are other information in the table.

Figure 6 - Percent Struck vs. Distance from Machine



The two major factors that cross tabulations showed to have an effect on the operator's ability to avoid being struck by the machine were the operators distance from the machine and the speed of the machine. The effect of the operators distance can be seen in figure 6. The differences in incident rates between a distance of 0.3-m and 0.6-m is small and can be accounted for by the randomness of the simulation but at 0.9-m the incident rate is significantly reduced. Figure 7 shows the effect of machine speed on incident rates. There is an almost linear reduction in rates as machine speed is reduced. These results are not surprising but do indicate that recommendations on speed and operator distance from the machine could reduce operator injuries. The interaction of these factors and the influence of other parameters were further explored in the survival analysis.

Figure 7 - Percent Struck vs. Machine Speed



Relative Risk

Based on the results of the Cox regression analysis, a model was developed that incorporated main effects and interactions of the independent variables on the time to contact. All main effects were found to be significant and 12 of 15 two-way interactions were significant, resulting in a complex risk model. In addition, the proportional hazards assumption was rejected in almost all cases, save for the machine speed variable, indicating that the hazards associated with most of these variables were changing with time.

Due to model complexity, analyses of relative risk were calculated while the machine was in motion at 0.1 s, 1 s and 3 s. The times were chosen based on the first time recorded, the time when 98% of the cumulative incidents have occurred and a time in the middle. Using only the five lowest and the five highest relative risks calculated at these times, tables 2 - 4 were compiled and included for each time period, distance, speed, work posture, facing orientation, work location, escape direction and relative risk. The coefficients in this model helped to evaluate the relative risk of experiencing a struck-by event at different points during the machine movement and showed the degree of influence for each variable in the model while controlling the effects of all other covariates.

DISCUSSION

Machine speed was the most influential variable in terms of explaining the struck-by event occurring. Increases in machine speed resulted in increased chance of being struck and the increased risk associated with higher speeds was constant throughout the times investigated in the study. In general, compared to the 4.77 deg/s condition (referent condition), the 9.75 deg/s speed increased risk threefold and the 19.1 deg/s condition increased risk by 8 times the referent value. The distance from the machine at the start of the test, also had a significant influence. The relative risk of being struck-by the machine, while working within 0.3-m, was the greatest at the beginning of the simulation.

Throughout the simulation the operator in a squat work posture was obviously at increased risk of being struck. In general, this posture was associated with an increase in relative risk that was 2.5 times the standing (referent) condition. It seems clear that this posture increased the time it took to escape. On the other hand, the kneeling posture was found to be the lowest in terms of relative risk of all the postures. This posture may have positioned the body in a manner to avoid being struck by the machine, and still allowed for a relatively quick escape via crawling. At the beginning of the simulation, a front-facing orientation revealed a higher relative risk, which appeared to be due to the propensity of subjects to turn around before moving away from the machine. The extra time associated with this maneuver may result in subjects being unable to successfully avoid contact with the continuous miner.

Table 2 – Lowest and highest relative risk at time 0.1 sec.

	m	Speed deg/s	Posture	Facing	Location	Dir deg	Relative risk
Lowest	0.9	4.77	standing	front	Drum	45	0.0017
	0.9	4.77	standing	front	Drum	90	0.0023
	0.9	4.77	standing	front	Drum	135	0.0023
	0.9	4.77	standing	front	Drum	180	0.0025
	0.9	9.75	standing	front	Drum	45	0.005
Highest	0.3	19.1	standing	right	Tail	180	45.79
	0.3	19.1	standing	right	Tail	135	42.62
	0.3	19.1	standing	right	Tail	90	41.55
	0.3	19.1	standing	left	Tail	180	32.89
	0.3	9.75	squatting	right	Tail	180	30.64

At later phases of the simulation (table 4), right-facing orientation becomes a lower relative risk. Except for machine speed, the relative risks associated with all variables were found to time dependent. This means that risks were found to be either increasing or decreasing with time for most variables, which explains why different activities were found to be higher risks at different points in the simulations.

The operator at the tail location is at a much higher relative risk compared to the drum location throughout the simulations. It should be noted that an operator location at the tail, drum or center portion of the machine are at risk of injury and all locations violate the red zone strategy, because tramming while positioned within the turning radius of the continuous miner can be fatal according to MSHA data (Dransite J and Huntley C., 2005). Unfortunately, the rotation of the machine around it's center point makes many think it would not lead to a risk of struck by accidents when the operator is so positioned. Like the other two locations, the center of the machine is not a safe location for the operator to be positioned, due to pinch points (MSHA 2006) should the machine slip toward the operator while tramming.

The tail and drum locations were the only locations used, because of the potential escape routes from within the turning radius of the machine. The data presented here suggest that greater risk is present when the operator is positioned near the tailpiece as opposed to the drum (in terms of struck by accidents). A possible explanation is that the linear velocity is greater at the tailpiece than the drum. However, positioning near the drum may have other consequences associated with it that may need to be considered. Relative risk of being struck-by the machine using the escape path direction 180° (path number 7) was the greatest throughout the simulation. It is clear that successful escape is less likely when moving parallel to the machine than when the escape vector has a component of motion that is away from the machine.

In summary, the data obtained in this study revealed a complex interaction of factors that affect the risk of struck by accidents when tramming continuous miners in an underground mining environment. However, the increased understanding of these relationships should ultimately result in recommendations such as reduced turning speeds and better training emphasis on the red-zone strategy so to decrease the risk of these potentially fatal accidents for continuous miner operators. Further study and analysis are required before specific recommendations can be made.

Table 4 – Lowest and highest relative risk: at time 3 seconds

	m	Speed, deg/s	Posture	Facing	Location	Dir deg	Relative risk
Lowest	0.6	4.77	squatting	right	Drum	90	0.0179
	0.6	4.77	squatting	left	Drum	90	0.0195
	0.3	4.77	kneeling	right	Tail	45	0.021
	0.3	4.77	kneeling	right	Tail	135	0.021
	0.3	4.77	squatting	right	Drum	90	0.0212
Highest	0.9	19.1	squatting	front	Tail	180	292.87
	0.9	9.75	squatting	front	Tail	180	291.18
	0.9	19.1	squatting	left	Tail	180	267.07
	0.9	9.75	squatting	left	Tail	180	265.53
	0.9	19.1	squatting	right	Tail	180	245.81

Table 3 –Lowest and highest relative risk: at time 1 seconds

	m	Speed deg/s	Posture	Facing	Location	Dir deg	Relative risk
Lowest	0.6	4.77	squatting	front	Drum	90	0.039
	0.6	4.77	squatting	left	Drum	90	0.0407
	0.6	4.77	squatting	right	Drum	90	0.0423
	0.3	4.77	squatting	front	Drum	90	0.0447
	0.3	4.77	squatting	left	Drum	90	0.0467
Highest	0.9	9.75	squatting	right	Tail	180	42.6
	0.9	9.75	squatting	left	Tail	180	40.97
	0.9	9.75	squatting	front	Tail	180	39.21
	0.3	9.75	squatting	right	Tail	180	30.5
	0.3	9.75	squatting	left	Tail	180	29.34

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